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A study on energy and CO_2 saving potential of ground source heat pump system in India

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ABSTRACT

In the past two decades, ground source heat pump (GSHP) system has made good impact on energy saving in the Western and European countries in heating/cooling and industrial applications. Their potential for reduction in CO_2 emission has been very well utilized by these countries to contribute to a green environment. In this paper an attempt is made to give an overview about how India can benefit from this technology. The economic growth of India has huge impact on energy and environment of the country. Though Indian building sector is growing in multifold, still there is a demand for electricity to meet the needs of people. Any technology to reduce energy consumption will have great impact on people′s life and economy. In this way a study has been carried out to estimate, to what extend the ground source heat pump technology can help India to reduce its energy demand and also save the environment. This study covers 10 provinces of northern part of India which require both heating and cooling. Based on the topography of the states, they are classified into severe winter states and moderate winter states for heating requirement. During winter period the conventional electric heaters consume electricity between 1416 and 7085 GW annually and for the same heating load GSHP consumes only 471–1416 GW. In summer months the electricity consumed by conventional air conditioner ranges between 5506 and 27,532 GW and by GSHP it varies from 4811 to 14,440 GW. The annual CO_2 emission by the conventional systems used for heating and cooling vary between 5270 and 26,352 million kg of CO_2. In the case of GSHP CO_2 emission lies between 4022 and 12,071 million kg. It is estimated that by employing GSHP technology India can save annually a minimum electricity of 1639–18,700 GW and CO_2 emission of 1.3–14.2 million tons.

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1. Introduction

1.1. Ground source heat pump

Around the world energy consumption for space conditioning is increasing every year; each country intends to reduce their energy consumption from fossil fuels due to green house gas emission and want to promote renewable energy technologies; most of the countries have established policies for promoting renewable energy. In developed and developing countries considerable amount of energy is being used for space heating and cooling; so, researchers are focusing on developing new technologies, which will reduce the energy consumption to meet the heating and cooling demand. Some of the important technologies are solar energy based heating and cooling system, net zero energy building, desiccant based space conditioning system, air source heat pump (ASHP) and ground source heat pump (GSHP) system. Among these technologies GSHP is very popular in Western and European countries for space heating. Both ASHP and GSHP work on the basis of vapor compression principle, but ASHP uses atmospheric air as source and sink for its heating and cooling applications, whereas in the case of GSHP the constant earth temperature is utilized for its applications. The coefficient of performance (COP) of the GSHP is higher than the ASHP and more or less its COP is constant but the COP of ASHP is affected by ambient air temperature.

GSHP can operate both in heating and cooling mode and the changing can be done by means of a reversing valve. During heating mode, GSHP absorbs heat from the ground and supplies to room. In cooling mode it absorbs heat from the room and rejects heat into the ground. The GSHP system can be either open loop system or closed loop system. In open loop system the main source or sink for the system is water bodies. Closed loop system can be further classified into horizontal system or vertical system. In a horizontal system high density polyethylene (HDPE) pipe is buried up to a depth of 5 m. In a vertical system, the borehole will be made in the ground up to certain depth and through this borehole, the heat exchanger will be installed. The depth of a vertical system will vary from 30 m to 300 m. Some GSHP systems will directly exchange heat with the ground through its refrigerant circuit. The performance of direct exchange GSHP system will be higher than all other systems but it has high degree of risk for leakages in the ground. The main objective of the present study is to review the use of GSHP in various applications in comparison to other technologies for space heating/cooling applications. Later an attempt is made to estimate the amount of saving in electricity and CO_2 emission by the use of GSHP in northern parts of India.

1.2. International and national scenario of installed GSHP system

A report published in 2009 [1] shows that as on 2005, 15.4 GW of GSHP systems are installed for heating and cooling applications around the world. The majority of the systems are installed in North America (USA, Canada) and in Europe. Sweden, Switzerland, German, France, Denmark, Finland, Austria and United Kingdom are the major European countries to use GSHP Technology. It has been reported [2] that around 20,000 GSHP units are installed every year around the world. The market share of GSHP system installed in Asia is only 5% [1] as on 2005; China, South Korea and Japan are the major countries to use GSHP technology in Asia. As per a study in South Korea [3], 127.1 MW of GSHP systems have been installed for heating and cooling applications. In China 2537 GSHP projects [2] are installed to meet the heating and cooling load of 20 million square meter of building area. More than 2 MW of GSHP projects are installed in Japan [4], however in India not even 1 MW of GSHP system has been installed till date but some foreign companies [5,6] have started their branches in India to utilize India's market potential. So it is necessary to develop a technology suitable for Indian climatic conditions for harvesting the ground source energy for heating and cooling applications. The works reported by Kumawat et al. [7,8] were some of the research initiatives in this direction. Sivasakthivel et al. [9] studied the electricity saving and CO_2 saving potential of GSHP system in India for space heating. They considered 10 states of northern part of India for analysis and they assumed only 10% of the families in a state use electric heater and GSHP system. Based on their analysis, it is found that by replacing the conventional electric heating system with GSHP system India could save about 708 GW of electricity and 0.539 million tons of CO_2 emission in a year. The major limitations of their study are, they considered states that require both heating and cooling but they considered only heating case and also they considered only 10% of families for using electric heater and GSHP. However, in the real case the number of families using these systems may be more, so there is a need for

Nomenclature

GSHP	ground source heat pump
COP	coefficient of performance
ASHP	air source heat pump
JNNSEM	Jawaharlal Nehru National Solar Energy Mission
HDPE	high density polyethylene
GW	giga Watt
TW	tera Watt
VAV	variable air volume
DXGSHP	direct exchange ground source heat pump
SAGSHP	solar assisted ground source heat pump
BHX	borehole heat exchanger
GWHP	ground water heat pump
EI	emission intensity
EH	electric heater
AC	air conditioner
TR	ton of refrigeration
kW	kilo Watt
MW	mega Watt
GHG	green house gases
HD	heating demand
CD	cooling demand
HGSHP	hybrid ground source heat pump
GHX	ground heat exchanger

a detailed study in this aspect. For both space heating and cooling applications, Prateek et al. [10] discussed about improvement potential, relative irreversibility, productivity lack and exergy destruction in a ground source heat pump system installed at IIT Roorkee which experiences a typical weather condition of northern part of India. From their analysis it was found that maximum relative irreversibility occurs in the condenser for both heating and cooling modes i.e. 41.74% and 33.56% respectively. In both the modes, exergy destruction and relative irreversibility are found to be less at evaporator, fan coil unit and the ground heat exchanger. Their study lacks on the aspect of how GSHP can help India to reduce its energy consumption and save environment and moreover their focus was only on theoretical study of GSHP based on Second law of thermodynamics.

1.3. GSHP for space heating and cooling

The applications of GSHP system for space heating and cooling in residential and commercial buildings have been carried out experimentally by a number of researchers in different countries for different climatic conditions. Kim et al. [11] studied the performance of GSHP system installed in a Korean school building. During their experiments they monitored the ground temperature at different depths. It was found that after 10 m of depth the ground temperature was not affected by the outside ambient temperature and in partial load operation the COP of heat pump in heating mode varied from 4.3 to 8.3. Flaga-Maryanczyk et al. [12] carried out experiments and CFD simulation of GHX system for space heating of a building located in Poland. The GSHP system was able to meet on an average of 15% of building heating load from November to April. Zhai et al. [13] carried out experimental trials on GSHP system for space cooling of a building located in Shanghai, China. It was found out that after 1 year of operation the soil temperature increased only by 0.5 °C and also they recommended multiple BHX with minimum length between the heat exchangers as 4–5 m. Yu et al. [14] conducted year round experimental study on GSHP system installed in Shanghai, China. Their results show that the GSHP system was able to meet the required building archives design code of China. Ozyurt and Ekinci [15] studied the performance of a vertical GSHP system for space heating in Turkey. During the 5 months of experimental trial runs, they noted that the condenser outlet temperature was at required level (i.e. 42–48 °C) and they suggested that for this kind of system floor heating is better than radiant heating. Michopoulos et al. [16] studied the operational performance of a GSHP system installed in Northern Greece for heating and cooling modes. They observed that during one cyclic operation the maximum seasonal COP was observed to be 5.2 and 4.5 for heating and cooling modes respectively. Naili et al. [17] studied the possible use of GSHP system for Tunisian climatic conditions. They evaluated the effect of different parameters on GHX performance and also the performance of GSHP system. Their results show that the heat exchange rate increases with increase in GHX but not in linear relation and also the mass flow rate of water flowing in the GHX also affects the heat transfer rate and the heat transfer rate was observed to be maximum at a flow rate of 0.12 kg s^{-1}. Karabacak et al. [18] studied the performance of a GSHP system for space cooling in Turkey. They used a system consisting of 225 m long vertical U tube heat exchanger installed at 110 m depth of borehole. During the operation they monitored solar radiation, wind speed, relative humidity and air temperature to correlate the performance of GSHP with these parameters. They concluded that increase in solar radiation decreased the COP of the system and wind speed also affected the COP significantly. Rate of heat transfer varied from 27 to 93 W/m during 5 months of operation. Park et al. [19] studied the cooling performance of a HGSHP system with different flow configurations and they compared with a GSHP system. Results show that the HGSHP system performance was 2–6.5% higher than the conventional GSHP system. Esen et al. [20] carried out an experimental study on a GSHP system installed in Turkey. They evaluated the performance by calculating the COP of the system and also created a numerical model to predict the temperature distribution in the vicinity of the heat exchanger and their numerical results are close to their experimental data. Aikins et al. [21] carried out a detailed study on the performance of a GSHP system in Republic of Korea. Their study reveals that the COP for cooling mode is higher than the heating mode and also they suggested some of the methods to improve the use of GSHP system in Korean market.

1.4. GSHP – green house heating and other applications

Other than space heating and cooling applications, GSHP can also be employed for other applications. Benli [22] used a GSHP system for green house heating in Turkey. For a green house area of 30 m^2, the length of horizontal GHX to meet the required heating demand was calculated to be 246 m. During October to May of 2005–2006, he carried out experimental trial runs and found that the GSHP was able to maintain the required temperature of 28 °C inside the green house. In another work, Benli [23] compared the performance of a horizontal and a vertical type of GSHP system for green house heating. Experimental results show that the vertical type of GSHP system is more efficient than the horizontal one. Ozgener and Hepbasli [24] carried out an experimental study on SAGSHP for green house heating. They found that during the operation of the system, the collector efficiency varied from 28% to 62% and also found that with the use of a scroll compressor an increase in COP was obtained compared to

a hermetic compressor. Esen and Yuksel [25] studied the possibility of using various renewable energy sources for green house heating and they considered bio gas, solar and GSHP system as heating options and carried out experiments from November 2009 to March 2010. During this period, the required temperature inside the green house was 23 °C. By considering all the heating options, they carried out a series of trial runs and found that all of them were able to maintain the required temperature and also the ground temperature was not reduced more than by 1 °C. Wang et al. [26] carried out experimental trial runs on a SAGSHP system combined with thermal energy storage. Their results indicate that after 1 year of storing, the heat pump was able to extract 75.5% of stored energy and also during heating operation the solar collector was able to supply 49.7% of total heating energy. Balbay and Esen [27] proposed a GSHP based bridge and pavements heating to clear snow during winter in Turkey. They used 30 m, 60 m and 90 m vertical borehole heat exchangers for heating purpose. The effect of depth of boreholes on the performance of GSHP for heating was also investigated. The results show that the GSHP system was able to successfully remove the snow from the bridges and the pavements. Wang et al. [28] carried out experiments on DXGSHP for space heating in Jinzhou, China. During the operation of the heat pump, the indoor room temperature varied from 18 to 20 °C and the average heat transfer was 54.4 W/m. The maximum and average COP of the system in heating mode was found to be 6.08 and 4.73 respectively. Kim et al. [29] studied the performance of HGSHP system. It consists of solar collector, CO_2 based heat pump unit and vertical heat exchanger unit. It was found that HGSHP system was more sensitive to heat pump operating temperature and when operating temperature was increased from 40 to 48 °C then the compressor work increased from 4.5 to 5.3 kW. Chen and Yang [30] proposed a SAGSHP system for space heating and hot water production. The proposed system was able to meet 75% of hot water requirement and complete building heating demand. Fernández-Seara et al. [31] studied the possible use of GSHP system for space heating and hot water production simultaneously. Their results show that entering water temperature at condensing unit plays a major role in the overall COP of the system.

1.5. Comparison of GSHP with other technologies

Esen et al. [32] studied the performance of GSHP system and its economic benefits compared to other conventional systems like electric heater, fuel oil, natural gas, liquid petrol gas, coal and oil. They found that during heating operation, the average COP of heat pump was 3.2 and GSHP is economically a good option compared to electric heater, fuel oil, coal, liquid petrol gas and oil but not as a good option compared to natural gas, because of plenty of availability of natural gas in Turkey. Esen et al. [33] carried out thermo economic comparison of ASHP and GSHP system for space cooling in Turkey. The GSHP systems consist of two different horizontal GHXs installed at 1 m and 2 m depth. Their results show that the COP of GSHP system installed at 1 m depth was 3.85, the COP of the system for 2 m depth was 4.26 and the COP of ASHP system was 3.17. The payback period for GSHP installed at 1 m depth was 3.7 years and for GSHP installed at 2 m depth was 4 years compared to ASHP system and the capital cost of ASHP system is less than the GSHP system but in the case of running cost the GSHP system was cheaper, so long term operation of GSHP systems are preferable. Pulat et al. [34] experimentally studied the performance of a horizontal GSHP system installed in Bursa, Turkey and also compared the unit cost of GSHP system with five different heating methods. It was found that the unit cost of GSHP system was very low; next to GSHP, natural gas heating is found to have very low unit cost and LPG and electric heater have the highest unit cost. Yang et al. [35] performed experiments on DXGSHP for space heating and cooling in Xiangtan, China and compared its performance with conventional GSHP system. The GHX used in this study was made of copper U tube with 42 m length. They found that DXGSHP performance is higher than the conventional GSHP system. Bakirci et al. [36] carried out energy analysis of SAGSHP system for space heating and they reported the economic and environmental benefits of SAGSHP system for Turkish climatic conditions. Lee et al. [37] carried out experimental trial runs on possible use of building foundation as a heat exchanger system compared to conventional vertical borehole system. Results show that the COP of the system varied from 3.9 to 4.3 and it is slightly lesser than the conventional vertical GSHP system but the cost of drilling is reduced by 83.7%. Badescu [38] discussed different economical aspects of using ground energy for passive house heating. They considered three cases, conventional heating system, conventional heating system combined with GHX and GSHP system. Results show that for longer period of operation (i.e. >3 years) GSHP and combined GHX are good options. Blumsack et al. [39] carried out an energy analysis of GSHP installed in Pennsylvania and compared with electricity based heating and cooling systems and heating oil furnace. They observed that GSHP was 43% more efficient than conventional electricity based cooling systems, 81% more efficient than electricity based heating systems and is 42% more efficient than heating oil furnace for heating and hot water production. Some of the researchers [40–47] have reported the benefits of geothermal heat pump systems.

1.6. GSHP – CO_2 emission studies

The use of GSHP for space heating results in saving in centrally generated electricity. Hence this results in indirect benefits on reduction in CO_2 emission. Bayer et al. [48] studied green house gas saving by the use of GSHP for 19 European countries, where one third of the global GSHP systems are installed. They calculated CO_2 saving of 3.7 million ton for the year of 2008 based on installed capacity and also they extrapolated the calculation for 2011 as 5.5 million tons of CO_2. Blum et al. [49] carried out CO_2 saving analysis of GSHP system for Southwest Germany. The CO_2 saving for regional and country electricity mix varies from 1.8 to 4 tons. The total CO_2 saving for all the installed 1105 GSHP systems is around 2000 tons of CO_2 per year. Genchi et al. [50] carried out an analysis to estimate the CO_2 payback period for replacing air source heat pump in Tokyo with GSHP system and also to calculate CO_2 saving. To estimate the payback time all the installation processes of GSHP system has been monitored; this process includes monitoring of CO_2 emission from transportation and installation of cooling tower, ground heat exchanger and digging of ground. The total CO_2 emission from GSHP installation is around 67.7 tons of CO_2, in this around 87% of CO_2 is emitted from digging process alone. The payback period for shifting from ASHP to GSHP is found to be 1.7 years; emission from ASHP for a year is 73.5 tons of CO_2 whereas, the saving in CO_2 by GSHP is 39.5 metric tons. Chai et al. [51] studied the performance of GSHP system for green house heating in Northern China. The COP of heat pump for heating was found to be 3.83 and the GSHP heating cost was 9% lower than the gas fired heating (GFH) system and 16.5% higher than the coal fired heating (CFH) system. GSHP was able to reduce the emission level by 42% compared to CFH system. Russo et al. [52] studied the possible use of GWHP system in Italy to reduce the energy cost and CO_2 emission by replacing the conventional gas fired and oil fired boilers. They considered 200 m^2 house with good insulation. Their results show that when GWHP was replaced with gas fired boiler it was able to save 36.34 tons of CO_2 and 51.9 tons of CO_2 by replacing oil fired boiler for 10 years of operation.

Studer [53] made an attempt to study saving in electricity and CO_2 emissions by the use of GSHP in Colorado and compared with conventional furnace and air conditioner. The study was carried out in 10 different locations of Colorado. The results show that in all the locations, the use of GSHP has saved electricity and considerable amount of CO_2 emission. Jenkins et al. [54] modeled the carbon saving potential of GSHP system for a single UK family house by replacing conventional gas boiler system. They considered three different outlet temperatures from the GSHP system. When the GSHP outlet temperature is 35 °C, the GSHP system was able to save 40% of CO_2 emission compared to conventional gas boiler. The CO_2 saving potential was reduced to 4% when the GSHP outlet temperature increased to 55 °C. Charoenvisal [55] studied the energy and economic performance of GSHP system installed in Knowledge Work Buildings I and II at Virginia Polytechnic Institute, Virginia, USA. Energy performance and life cycle cost of GSHP and other two alternatives (variable air volume (VAV) with hot water coil heating and air-source heat pump system) were studied using eQUEST software. Their results indicate that the GSHP was able to save 124 MWh energy annually compared to VAV system and 69.3 tons of CO_2. Kikuchi et al. [56] studied different residential energy systems options for GHG reduction in five Canadian cities. They considered GSHP, photovoltaics and energy efficient appliances with different combinations as options and they proposed different combinations for different cities based on the available energy sources. Hanova et al. [57] examined the potential of GSHP in reducing GHG emission and economic benefits at provincial level in Canada. Compared to electric heater, gas and oil heating systems, GSHP was able to save GHG emission at all Canadian provinces. The savings varied from 0.3 to 22.3 tons of CO_2 and cost from \$500 to \$2500 depending upon the fuels and the provinces.

1.7. GSHP performance studies

Schibuola et al. [58] carried out a study on GSHP system in high humid soil for different borehole arrangements (i.e. single U tube and double U tube). Their results show that the heat exchangers operating in humid soil are more efficient than those operating in less humid soil and the reason for this high soil thermal conductivity and high heat capacity of soil. Luo et al. [59] studied the energy loss in horizontal ground loop system. They considered burial depth and pipe insulation as parameters and they found that these parameters play a major role in energy loss and they suggested that 25 mm insulation thickness can avoid 50% of energy loss in horizontal loop. Rezaei et al. [60] studied the performance of GSHP with Tire Derived Aggregate (TDA). Their results indicate that TDA was able to improve the extraction rate of heat exchanger by 17%. Casasso and Sethi [61] studied the efficiency of a closed loop GSHP system by considering different GSHP parameters. They concluded that among the different parameters, the length of the heat exchanger played a major role and also thermal conductivity of soil should be properly evaluated and it should not go by assumption. Luo et al. [62] studied the performance of BHX with three different diameters of borehole and also economic viability of each borehole. They concluded that BHX with large borehole diameter has good thermal performance but for thermo-economical benefits, smaller borehole diameters are the best options. Montagud et al. [63] carried out modeling and experimental analysis of GSHP system. Modeling of GSHP was done in GLHEPRO and the results of modeling analysis were compared with experimental results. It was observed that the ground was able to recover much faster than what was predicated in modeling. Choi et al. [64] studied the performance of GSHP with single U tube and double U tube heat exchangers. Their results show that during the initial period of operation the performance of both the heat exchangers are observed to be at the same level. In long term operation, the double U tube heat exchanger performance i.e. heat extraction rate from the ground was decreased. Zhai et al. [65] carried out optimization of GSHP system for different indoor set temperatures. Based on their analysis they suggested that indoor temperature at 22–24 °C is optimum, at this optimum temperature thermal imbalance of the ground is very minimal. Kjellsson et al. [66] optimized the vertical GSHP system combined with solar collector installed in a dwelling. The aim of the study was to find the optimal combination of GSHP and solar collectors for heating and hot water production. The best combination observed was; use the solar collector for hot water production in summer and for recharging the ground in winter. Zogou and Stamatelos [67] studied the effect of climatic conditions on the design optimization of heat pump systems. They considered the northern and southern parts of Europe for their analysis. The study reveals that milder climates of the Mediterranean and subtropical climates are more favorable for the use of heat pump systems. Thermo-economic optimization of horizontal and vertical ground coupled heat pump system carried out by a number of researchers [68–72] to reduce the cost of the system.

A detailed literature survey on GSHP heating and cooling applications and emission studies indicates that most of the developed and developing countries are now focusing on GSHP as an alternate technology for reducing the consumption of centrally generated electricity for space heating and cooling applications and thereby to achieve reduction in CO_2 emission. However, in the case of India not much technological change has taken place on systems used for space heating/cooling applications and thereby every year there is an increase in demand for centrally generated electricity for space conditioning. The awareness on the use of GSHP technology has been picking up in a slow pace. Hence in this paper an attempt is made to highlight the benefits of using GSHP system for Indian climatic conditions.

2. Background

2.1. Topography and climate of India

India is a South Asian country with land area of 3,287,263 km^2, about 2.42% of the world land area and it is the seventh largest

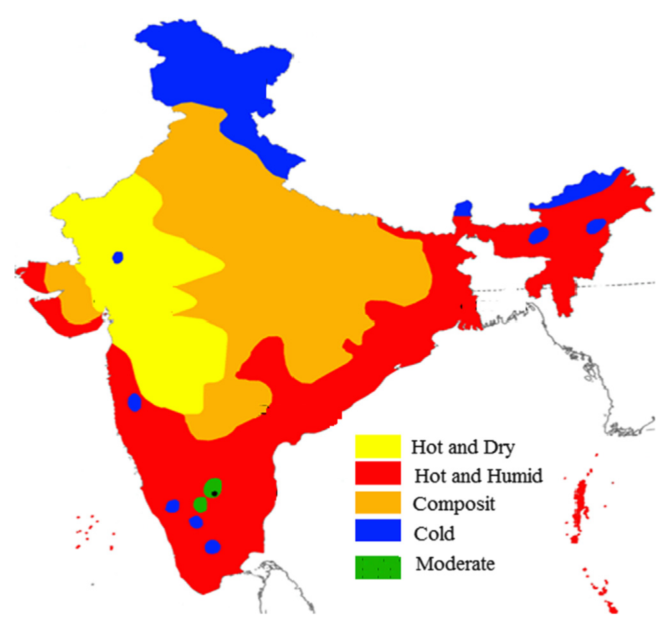

Fig. 1. Climate zones of India [73].

Table 1
Power generation in India by different fuels as on April 2013 [77].

Fuel	Percentage
Thermal (*Coal, Gas and Oil*)	66.9
Hydro	18.6
Nuclear	2.3
Renewable Energy Sources	12.2
Total	100
Total installed capacity	211.77 GW

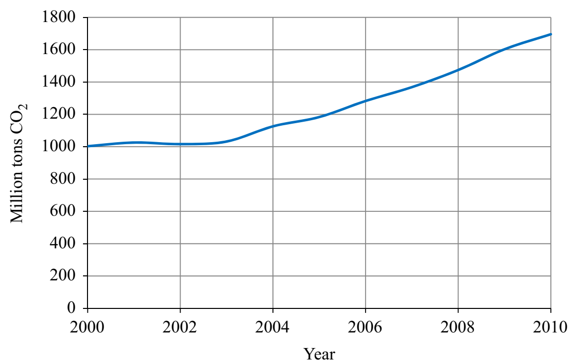

Fig. 2. CO_2 emission of India [81].

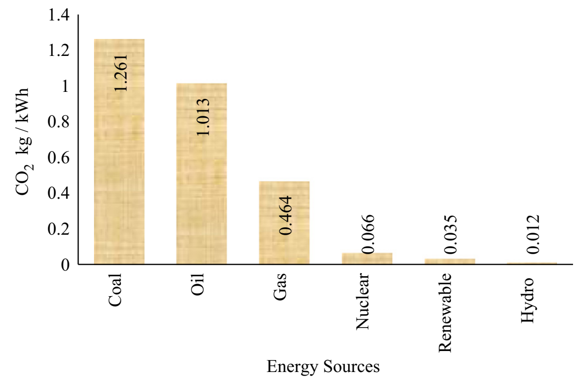

Fig. 3. Emission intensity of energy sources for electricity generation in India.

country on the earth, it shares international border with Pakistan, Nepal, Bhutan, China, Myanmar and Bangladesh. India's latitude and longitude lie between 8°4′N to 37°6′N and 68°7′E to 97°25′E. Fig. 1 [73] shows the climate zones of India. Based on the weather conditions it has been divided into five zones, hot and dry; states coming under this category are part of Rajasthan, part of Gujarat, western Madhya Pradesh, and central Maharashtra; the states coming under hot and humid regions are Kerala, Tamilnadu, Andhra Pradesh, Karnataka, part of Maharashtra, part of West Bengal, part of Gujarat, Assam, Nagaland, Mizoram, Tripura, Meghalaya and Manipur. Composite climate zone of India covers Punjab, Haryana, Uttar Pradesh, Bihar and part of Rajasthan. Sikkim, Arunachal, Jammu and Kashmir, Himachal Pradesh and Uttarakhand come under cold climate zone. In moderate climate zone Bangalore and its nearby areas are covered.

2.2. Indian building sector and its electricity consumption

Economic growth of India has helped to increase people's living standard and also it helped to increase India's commercial and residential building capacity. In 2010 India's total build up area was 659 million square meters and it is projected to reach 1900 million square meters by 2030, an increase of 66% [74]. Indian building sector is the second power consuming sector after industrial sector. In industrial sector around 46% of power is being consumed and in building sector it is around 29% [74]. Building sector in India can be classified into two segments, residential building and commercial building. In residential sector around 45% of power is being utilized for space conditioning (i.e. heating and cooling). In the case of commercial sector around 32% of power is used for heating, ventilation and air conditioning [75]. As per the study published in 2004 [75], annual electricity consumption in residential sector is 116 TWh and commercial sector is 33 TWh in 2001. Any measure to reduce this power consumption will help India to meet the increasing electricity demand and to reduce its CO_2 emission level.

2.3. Electricity generation and CO_2 emission of India

India has shown significant economic growth in the last 10–15 years and it is expected to grow the same way for another 10–15 years. Due to this economic boom India's energy demand has increased multifold. At the time of independence (August 1947) the total installed power capacity was 1363 MW [76] and at present it is 211.77 GW (as on April 2013) [77]; it makes India as fifth major power producer in the world. Power generation in India by different fuels is shown in Table 1. This table shows that the majority of power, around, 66.9% is being generated by thermal power plant. The power productions from hydro, nuclear and renewable energy are, 18.6%, 2.3% and 12.2% respectively. Even with this capacity India is striving hard to meet its electricity demand. The increase in demand and limited resources made policymakers shift the focus on renewable and nuclear energy. Some of the major initiatives are Indo-US nuclear energy deal and Jawaharlal Nehru National Solar Energy Mission (JNNSEM). India is set-to produce 20,000 MW by JNNSEM by 2022 [78] and about 60,000 MW of nuclear power by 2030 [79]. As most of the power generation in India comes from fossil fuel supported thermal power plants, globally India ranks 3rd in terms of CO_2 emission [80]. Fig. 2 shows the CO_2 emission of India for 10 years; in 2010 CO_2 emission was 1602.12 million tons; it is 5.27% of world CO_2 emission in that year. The forecast shows that by 2030 India's CO_2 emission will reach 3084 million tons [81]. India's energy consumption and emission level are increasing year by year; building sector is one of the important sectors, where 29% energy is used for heating and cooling and it is projected to increase every year. Any technology which will reduce this energy consumption will have good impact on India's energy security. In that way GSHP is an important alternative technology to the conventional systems. In this paper a study has been carried out to estimate the current energy consumption and emission level of conventional systems and also saving in electricity and CO_2 by shifting from conventional electric heating and air conditioner to GSHP technology. To carry out this study 10 Indian States whose climate zones are cold and composite are considered. The methodology used to carry out this study and possible saving in electricity and CO_2 emission are discussed in the following sections.

3. Methodology

3.1. Emission intensity of energy sources

In order to estimate the CO_2 emission from GSHP and other conventional system it is important to know the emission intensity of different fuels. The emission intensity [80] of different energy sources used for electricity generation in India is given in

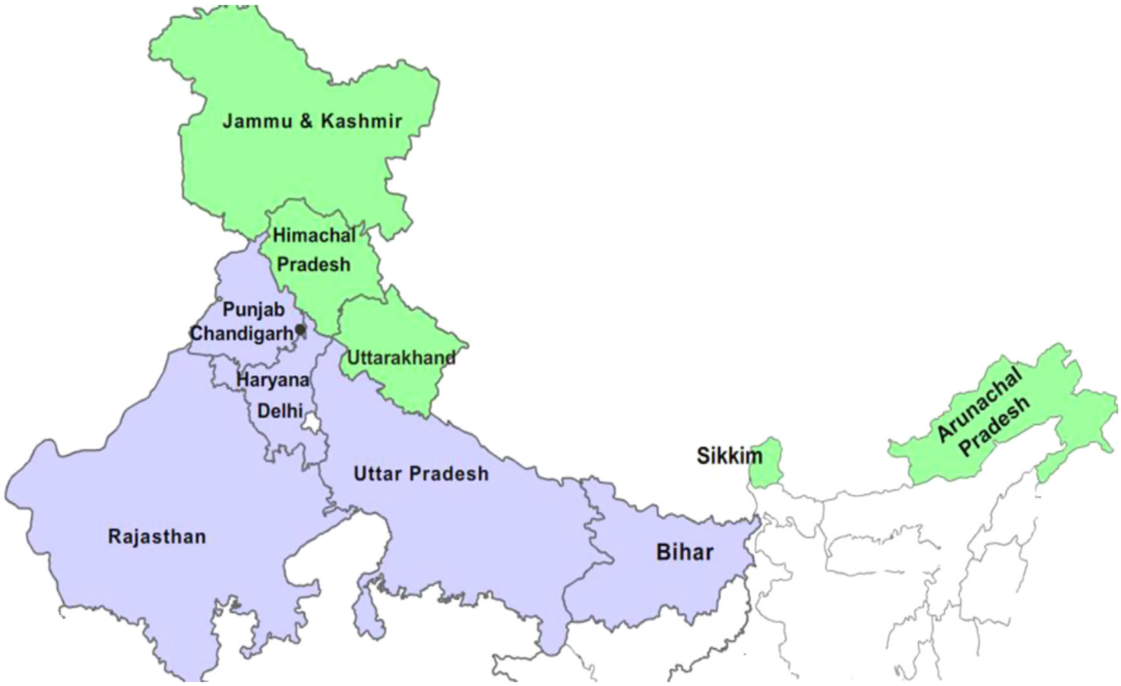

Fig. 4. Severe winter states in green and moderate winter states in purple. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. The emission intensity of power produced by coal is very high because Indian coals have low calorific value and high emission index [80]. The major CO_2 emitter of Indian power sector is power produced from coal, it is around 1.261 kg/kWh, the emission of oil is 1.013 kg/kWh but the power generation from oil based power plant is only 0.65%. The emission rate of gas power plant is 0.464 kg/kWh; however, the power produced from gas power plant is only 9.5%. The emission from renewable energy and hydropower plants are 0.035 and 0.012 kg/kWh respectively.

3.2. Modeling of power consumption for heating and cooling applications

Indian climatic conditions are varying from region to region but most of the regions require only cooling and some of the regions require both heating and cooling. In India winter season starts from late November and ends in middle of March. In this paper 10 north and northeast regions of Indian states are considered, and these states are classified into two categorizers, severe winter states (i.e. Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh) and moderate winter states (i.e. Punjab, Haryana, Uttar Pradesh, Rajasthan and Bihar). In severe winter states the required heating period is considered as 45 days because these states are located near Himalayas, so during winter they experience longer winter days and for moderate winter states, this period is 30 days. The summer falls during the months of April, May, June and July. The cooling requirement for all these 10 states can be taken as 90 days; these days are minimum number of days and in actual case, they may be higher. Fig. 4 shows the 10 states under two categories, in which the green color indicates the severe winter states and light purple color indicates states that are experiencing moderate winter.

The power consumption for space heating and cooling is calculated based on the population. The populations of these states are taken from census 2011 [82] and the family size is taken as 5, rounded off from 4.8 as defined by Ministry of Family Welfare [83]. From the total population, the total number of families is calculated for 10 states. The calculation of heating and cooling load is carried out on the basis of percentage of families that uses electric heater and air conditioner, in this study it is considered 10%, 30% and 50% of families use electric heater and air conditioner to meet their heating and cooling demand. The capacity of the heater is assumed to be 1 kW and assumed 100% efficient and is used for 5 h in a day during winter period. In summer months it is considered that each family is using 1 ton of air conditioner with two stars rating for cooling needs for 5 h a day for 90 days and it is assumed that this air-conditioner consumes 1.34 kW of electricity for producing 1 ton of cooling effect. Eqs. (1)–(6) are used to calculate the power consumption by electric heater, air conditioner and GSHP system with different COPs.

Power consumption in severe winter states by E.H.

$$= \frac{\text{population}}{\text{house hold size}} \times \%\,\text{family} \times 1 \times 5 \times 45 \tag{1}$$

GSHP power consumption in severe winter states

$$= \frac{\text{population}}{\text{house hold size}} \times \frac{\%\,\text{family} \times 1 \times 5 \times 45}{\text{COP of GSHP}} \tag{2}$$

Power consumption in moderate cold states by E.H.

$$= \frac{\text{population}}{\text{house hold size}} \times \%\,\text{family} \times 1 \times 5 \times 30 \tag{3}$$

GSHP power consumption in moderate cold states

$$= \frac{\text{population}}{\text{house hold size}} \times \frac{\%\,\text{family} \times 1 \times 5 \times 30}{\text{COP of GSHP}} \tag{4}$$

Power consumption in summer by A.C.

$$= \frac{\text{population}}{\text{house hold size}} \times \%\,\text{family} \times 1.34 \times 5 \times 90 \tag{5}$$

GSHP power consumption in summer

$$= \frac{\text{population}}{\text{house hold size}} \times \frac{\%\,\text{family} \times 1\text{TR} \times 5 \times 90}{\text{COP of GSHP}} \tag{6}$$

$$\text{Saving in power} = \text{power consumed by E.H.} + A.C. - \text{power consumed by GSHP} \tag{7}$$

Table 2
Power consumption for space heating by electric heater and GSHP for severe winter states and power saving by GSHP.

State	Population (millions)	Families (millions)	Power consumption for winter season (45 days) by electric heater (GW)			Power consumption and saving by GSHP for COP=3 (GW)						Power consumption and saving by GSHP for COP=4 (GW)						Power consumption and saving by GSHP for COP=5 (GW)					
			10%	30%	50%	10%		30%		50%		10%		30%		50%		10%		30%		50%	
						C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S
SK	0.6	0.12	2.7	8.2	13.6	0.9	1.8	2.7	5.4	4.5	9.1	0.68	2.0	2.0	6.1	3.4	10.2	0.5	2.1	1.6	6.5	2.7	10.9
AR	1.3	0.27	6.2	18.6	31.1	2.0	4.1	6.2	12.4	10.3	20.7	1.5	4.6	4.6	13.9	7.7	23.3	1.4	4.9	3.7	14.9	6.2	24.8
HP	6.8	1.37	30.8	92.5	154.2	10.2	20.5	30.8	61.7	51.4	102.8	7.71	23.1	23.1	69.4	38.5	115.7	6.7	24.6	18.5	74.0	30.8	123.4
UK	10.1	2.02	45.52	136.5	227.6	15.1	30.3	45.5	91.0	75.8	151.7	11.3	34.1	34.1	102.4	56.9	170.7	9.1	36.4	27.3	109.2	45.5	182.0
JK	12.5	2.50	56.4	169.4	282.3	18.8	37.6	56.4	112.9	94.1	188.2	14.1	42.3	42.3	127.0	70.5	211.7	11.2	45.1	33.8	135.5	56.4	225.8

SK: Sikkim, AR: Arunachal Pradesh, HP: Himachal Pradesh, UK: Uttarakhand, JK: Jammu and Kashmir, C: Consumption, S: Saving.

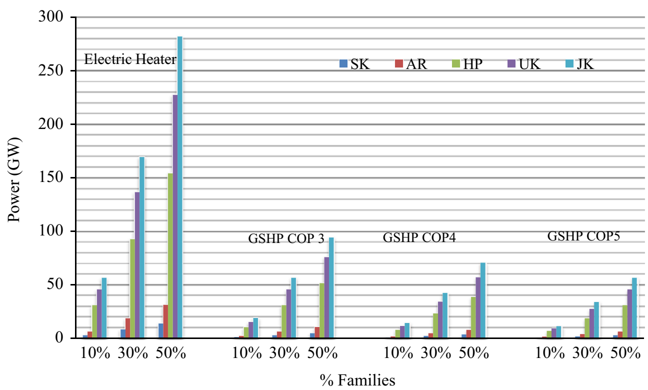

Fig. 5. Power consumption for space heating by electric heater and GSHP for severe winter states.

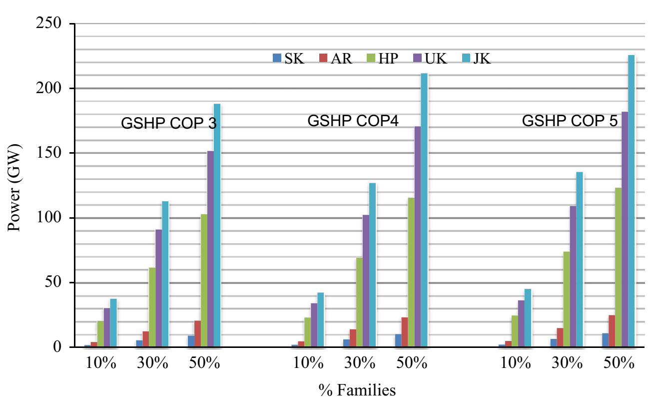

Fig. 6. Power saving by GSHP for space heating for severe winter states.

3.3. *Modeling of CO_2 emission for heating and cooling applications*

In India during winter and summer generally the conventional systems such as electric heaters and air-conditioners, are used to meet the demand of heating and cooling. The CO_2 emission calculations are carried out for winter and summer days based on the power consumption. To calculate the emission from the conventional and GSHP system, Eqs. (8)–(11) are used. In India majority of the power is produced from thermal power plant, and hence in this study overall India's power generation pattern is applied for all the states, instead of using individual state power generation model. Emission intensity of different energy fuels used in India's power plants is already presented in Fig. 3.

$$\mathrm{CO_2\ emission\ by\ E.H.} = \mathrm{H.D.} \times \mathrm{no.\ of\ families} \times \frac{\mathrm{operating\ hours}}{\mathrm{year}} \times \frac{\mathrm{E.I.\ of\ energy\ source}}{\mathrm{kWh}} \quad (8)$$

$$\mathrm{CO_2\ emission\ by\ A.C.} = \mathrm{C.D.} \times \mathrm{no.\ of\ families} \times \frac{\mathrm{operating\ hours}}{\mathrm{year}} \times \frac{\mathrm{E.I.\ of\ energy\ source}}{\mathrm{kWh}} \quad (9)$$

$$\mathrm{CO_2\ Emission\ by\ GSHP\ in\ winter} = \mathrm{H.D} \times \mathrm{No.of.\ families} \times \frac{\mathrm{operating\ hours}}{\mathrm{year}} \times \frac{\mathrm{E.I.\ of\ energy\ source}}{\mathrm{kWh}} \quad (10)$$

$$\mathrm{CO_2\ emission\ by\ GSHP\ in\ summer} = C.D. \times \mathrm{no.\ of\ families} \times \frac{\mathrm{operating\ hours}}{\mathrm{year}} \times \frac{\mathrm{E.I.\ of\ energy\ source}}{\mathrm{kWh}} \quad (11)$$

$$\mathrm{Saving\ in\ CO_2\ emission} = \mathrm{CO_2\ emission\ by}\ \{E.H. + A.C. - \mathrm{GSHP\ in\ winter\ \&\ summer}\} \quad (12)$$

4. Results and discussions

Using Eqs. (1)–(7) the electricity demand for space heating and cooling have been computed for both categories of states in India. The total CO_2 emission due to the electricity demand for space heating and cooling is estimated using Eqs. (8)–(12). The details of the results obtained are discussed in the following sections.

4.1. *Space heating*

Space heating requirement of north and northeast regions of India varies from state to state. In general in India winter secession starts from late November and ends in March. The peak winter months are December and January.

4.1.1. *Power consumption by electric heater and GSHP for severe winter states*

In severe winter category, five Himalayan states are considered, that are Sikkim (SK), Arunachal Pradesh (AR), Himachal Pradesh (HP), Uttarakhand (UK) and Jammu and Kashmir (JK). The states are named in the order of population, lower to higher level. Among these five states Sikkim has the lowest population of 0.6 million and Jammu and Kashmir has a population of 12.5 million [82]. The number of families in Arunachal, Himachal and Uttarakhand are 0.27, 1.37 and 2.02 million, respectively. As per the

Table 3
Power consumption for space heating by electric heater and GSHP for moderate winter states and power saving by GSHP.

States	Population (millions)	Families (millions)	Power consumption for winter season (30 days) by electric heater (GW)			Power consumption and saving by GSHP for COP=3 (GW)						Power consumption and saving by GSHP for COP=4 (GW)						Power consumption and saving by GSHP for COP=5 (GW)					
			10%	30%	50%	10%		30%		50%		10%		30%		50%		10%		30%		50%	
						C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S
HR	25.3	5.07	76.0	228.1	380.2	25.3	50.7	76.0	152.1	126	253.5	19.0	57.0	57.0	171.1	95.0	285.2	15.2	60.8	45.63	182.5	76.0	304.2
PB	27.7	5.5	83.1	249.3	415.5	27.7	55.4	83.1	166.2	138.5	277.0	20.7	62.3	62.3	186.9	103	311.6	16.6	66.4	49.8	199.4	83.1	332.4
RJ	68.6	13.7	205.8	617.5	1029	68.6	137	205	411.7	343	686.2	51.4	154	154	463.1	257.3	771.9	41.1	164.6	123.5	494.0	205.8	823.4
BR	103.8	20.7	311.4	934.2	1557	103	208	311	622.8	519	1038	77.8	233	233	700.6	389.2	1167.7	62.2	249.1	186.8	747.3	311.4	1245.6
UP	199.5	39.9	598.7	1796	2993	199.5	399.1	598.7	1197.4	997.9	1995.8	149.6	449	449	1347	748.4	2245.2	119.7	478.9	359.2	1436.9	598.7	2394.9

HR: Haryana, PB: Punjab, RJ: Rajasthan, BR: Bihar, UP: Uttar Pradesh, C: Consumption, S: Saving.

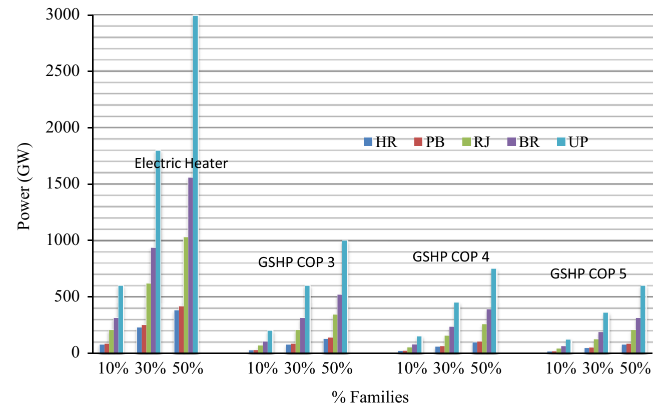

Fig. 7. Power consumption for space heating by electric heater and GSHP for moderate winter states.

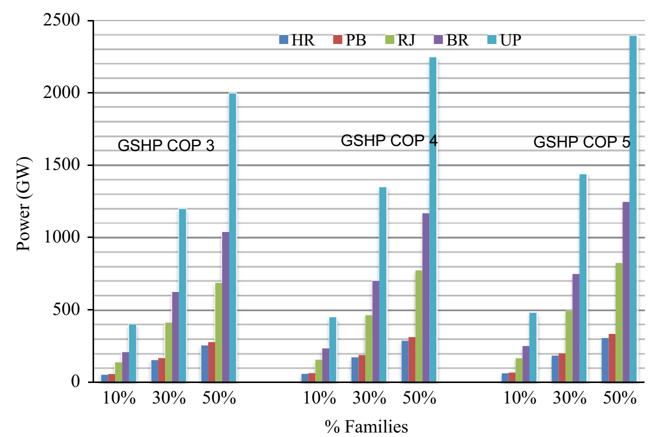

Fig. 8. Power saving by GSHP for space heating for moderate winter states.

model proposed in this paper, if 10%, 30% and 50% families are assumed to use electric heater for space heating purpose then the total electricity consumptions varies from 141.62 GW to 708.8 GW. This calculation is repeated assuming GSHP is used for the same heating load with varying COP and found that for 10% family the electricity consumption decreases from 47 GW to 28.9 GW as the COP increases from 3 to 5 and for 30% family it decreases from 141.6 GW to 84.9 GW as the COP increases from 3 to 5 and when 50% of families are using GSHP for heating purpose with varying COP 3–5 then the electricity consumption decreases from 236.1 GW to 141.6 GW. The power consumption of individual states for different percentage of usage and for different COPs is presented in Table 2. Fig. 5 depicts the comparison of electricity consumption by the electric heaters and the GSHP for individual severe winter states.

4.1.2. Power saving by GSHP for severe winter states

Ground source heat pump technology is well recognized in western and European countries for space heating purpose. With the help of this sustainable technology these countries have achieved a significant reduction in grid electricity consumption and indirectly helping to avoid addition of further green house gases to the environment. In this study it has been shown that by the use of GSHP technology in severe winter states, each state was able to save considerable amount of electricity as shown in Fig. 6. In all these states, for 10% families with COP of 3 the use of GSHP has resulted in electricity saving of 94.3 GW annually. When the GSHP is assumed to operate at COP of 5 then the total electricity

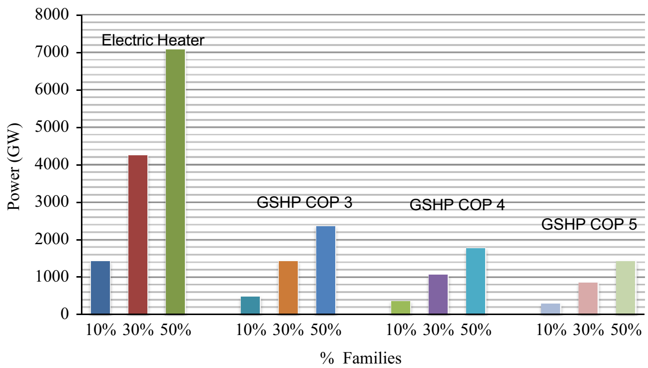

Fig. 9. Comparison of power consumption by electric heater and GSHP for space heating.

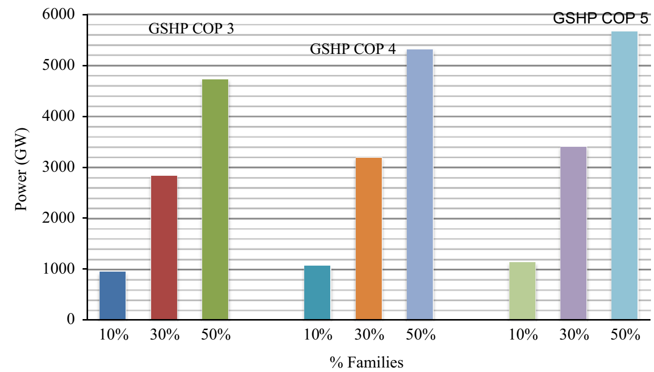

Fig. 10. Power saving by GSHP for space heating.

saving is found to be 113.1 GW. With an increase in GSHP COP from 3 to 5, the total annual electricity saving is increased by 18.8 GW, an increase of 16.7%. If 50% of the families are assumed to use GSHP for meeting the heating demand then the minimum possible electricity saving is found to be 472 GW for COP of 3 and 566.9 GW for COP 5. If we rank the states on the basis of electricity saving from higher to lower, then the states can be ordered as, Jammu & Kashmir, Uttarakhand, Himachal, Arunachal and Sikkim and this is because the families in JK is more than the families in SK. Individual state's saving potential in terms of percentage family for different COP's is presented in Table 2 and Fig. 6. In the case of Uttarakhand possible electricity saving on annual basis varies from 32.3 GW to 182 GW.

4.1.3. Power consumption by electric heater and GSHP for moderate winter states

The moderate winter states considered are Haryana (HR), Punjab (PB), Rajasthan (RJ), Bihar (BR) and Uttar Pradesh (UP) and the population and families of these states are presented in Table 3. Among these states Haryana has less number of families compared to Uttar Pradesh, which has the maximum number. The number of winter days in these states is less than the Himalayan states, during this small number of winter days people use inefficient electric heater for heating. As per our modeling estimation the power consumed by these states by considering only 10% families use electric heater, the power consumption comes to be 1275 GW in a year and for 50% of the families, the electricity consumption is 6375.7 GW. By any means if we are able to meet this heating demand by GSHP then the possible electricity consumption will be between 425 GW to 1275 GW. These estimated values are for 10% of families using GSHP with COP of 3 and 50% families using GSHP with COP of 5. Individual state's electricity consumption for using electric heater and GSHP are presented in Table 3 and Fig. 7. This table gives an overview about how the percentage of family usage alters the electricity consumption pattern and also for how different COP of GSHP will affect the electricity consumption.

4.1.4. Power saving by GSHP for moderate winter states

Moderate winter states consume more power than the severe winter states, the reason being the large size of these moderate winter states and large number of families. Rajasthan is the biggest state in India by land area and Uttar Pradesh is the most populated state in India, the population of UP is equivalent to the population of Brazil [84], which is world's fifth largest country. In any case these states can save electricity between 850 GW and 5100 GW annually. Possible electricity saving for individual states in different categories is presented in Table 3 and Fig. 8. Among these states Uttar Pradesh can save electricity between 399 GW and 2395 GW. In the case of Haryana, Punjab, Rajasthan and Bihar the range of electricity saving potential are 50–304 GW, 55–332 GW, 137–823 GW and 207–1245 GW, respectively.

4.1.5. Power consumption by electric heater and GSHP for space heating

The total power consumption in north and northeastern states of India is discussed here. Winter days in theses 10 states varies from region to region but all these states require both heating and cooling. As per the current situation the electricity consumed in these 10 states to meet the annual heating demand by electric heater varies from 1416 GW to 7085 GW. If the same heating demand is met by GSHP with different COP's then the electricity consumption varies from 471 to 2361 GW for COP of 3 and 353 to 1770 GW for COP of 4 and 283 to 1416 GW for COP of 5. Fig. 9 shows the electricity consumption by electric heater and GSHP for 10%, 30% and 50% of family use with different COP of GSHP.

4.1.6. Power saving by GSHP for space heating

On an average GSHP is found to be 3–6 times more efficient than the conventional electric heating systems. In India the conventional heating systems are electric heater, coal and wood burning stoves and biomass systems. The analysis shows that if all of these 10 states use GSHP for their heating then the potential power saving ranges from 944 GW to 5668 GW, for 10% of families using GSHP with COP 3, to 50% families use GSHP with COP of 5. Fig. 10 shows the possible power saving by GSHP for different COP and for different percentage of family use. When GSHP COP increases from 3 to 4, then the power saving for 10% family increases by 118.08 MW, an increase of 12.5% of power saving of COP 3, if COP increases from 3 to 5, then the saving potential increase by 20%.

4.1.7. CO_2 produced by electric heater and GSHP for space heating

In global ranking India is third in CO_2 emission and Indian government is also planning to reduce its emission level. The total power consumption in India for space heating varies from 1416 GW to 7085 GW for 10% of the families to 50% of families using electric heater for space heating. These values are only for the 10 states considered. Table 4 shows the possible CO_2 emission by electric heater and GSHP for different values of COP and different percentage of family usage in the states considered. CO_2 emission from thermal power plant for electric heater based space heating is around 1067 million kg for 10% of family use and 5336.77 million kg for 50% family use. Emission produced by hydro, nuclear and renewable energy sources for 10% family, who are using electric heater for space heating are 3.53, 2.39 and 5.35 million kg, respectively and the total CO_2 produced by

Table 4
CO_2 produced by electric heater and GSHP for space heating and CO_2 saving by GSHP.

CO_2 produced by different energy sources	CO_2 produced by electric heater (million kg)			CO_2 produced by GSHP for COP = 3 (million kg)			CO_2 produced by GSHP for COP = 4 (million kg)			CO_2 produced by GSHP for COP = 5 (million kg)		
	10%	30%	50%	10%	30%	50%	10%	30%	50%	10%	30%	50%
Coal	995.58	2986.8	4978.09	331.86	995.61	1659.36	248.89	746.71	1244.52	199.11	597.36	995.61
Gas	62.45	187.38	312.30	20.81	62.46	104.10	15.61	46.84	78.07	12.49	37.47	62.46
Oil	9.32	27.99	46.65	3.10	9.33	15.55	2.33	6.99	11.66	1.86	5.59	9.33
Hydro	3.53	10.59	17.65	1.17	3.53	5.88	0.88	2.64	4.41	0.70	2.11	3.53
Nuclear	2.39	7.18	11.97	0.79	2.39	3.99	0.59	1.79	2.99	0.47	1.43	2.39
Renewable Energy	5.35	16.06	26.78	1.78	5.35	8.92	1.33	4.01	6.69	1.07	3.218	5.35
Total CO_2 produced	1078.65	3236.05	5393.45	359.55	1078.68	1797.82	269.66	809.01	1348.36	215.73	647.21	1078.69
CO_2 saving (million kg)				*719.1*	*2157.37*	*3595.63*	*808.99*	*2427.04*	*4045.09*	*862.92*	*2588.84*	*4314.76*

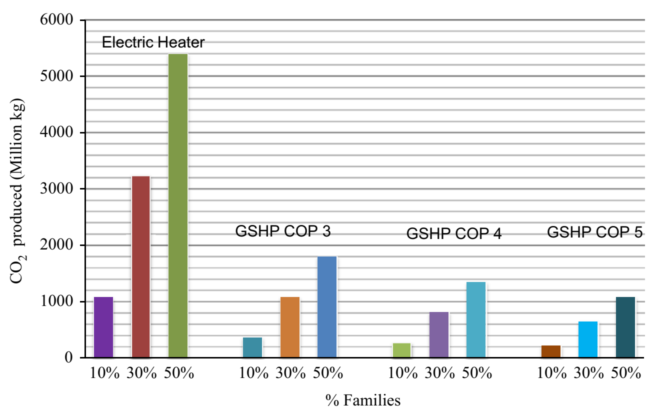

Fig. 11. CO_2 produced by electric heater and GSHP for space heating.

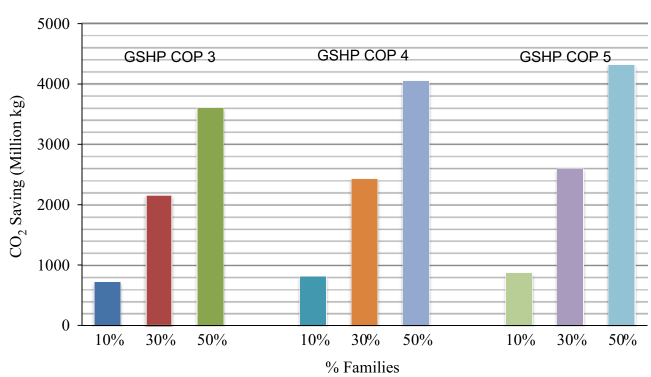

Fig. 12. CO_2 saving by GSHP for space heating.

electric heater for 10% family use is around 1079 million kg. For the case of 50% families using electric heater the possible CO_2 emission is around 5393 million kg. The CO_2 emission by GSHP for 10% family use with COP of 3 is 360 million kg and CO_2 emission for 50% family using GSHP with COP of 5 is around 1078.69 million kg. When COP of GSHP increases from 3 to 5, then the total CO_2 emission for 30% family use is decreased by 431.47 million kg. Fig. 11 shows the CO_2 emission from electric heater and GSHP. CO_2 emitted by coal, gas, oil, hydro, nuclear and renewable energy based power plants for electric heater and GSHP are presented in Table 4.

4.1.8. CO_2 saving by GSHP for space heating

Annual CO_2 saving by GSHP for space heating by different COP are presented in Fig. 12 and Table 4. The minimum possible CO_2 saving by GSHP for 10% family use with COP of 3 is 719 million kg and maximum possible CO_2 saving by GSHP for 50% family use with COP of 5 is around 4316 million kg. Increase in COP of GSHP from 3 to 4 results in an increase in CO_2 saving by 90 million kg and further increase in COP from 4 to 5 yields only 54 million kg for 10% family use.

4.2. Space cooling

In developed and developing countries space cooling is an important energy consuming sector. India's economic growth has helped to increase in building space and to improve the life style of the people. The 10 north and northeastern states considered in the present paper also experience severe summer hence require space cooling in summer. In general majority of Indian states requires mainly cooling. Researchers are working to develop new technology to provide cooling at reasonable energy consumption, in recent days solar energy based cooling is also gaining importance.

4.2.1. Space cooling – power consumption by AC and GSHP

In general, most of the commercial and residential buildings in India are using conventional air conditioners for space cooling, in such situations GSHP can be a good alternative technology to provide heating, cooling and hot water production. Energy consumption for cooling has been computed by considering 90 days as the cooling period for all the 10 states considered. Table 5 presents the power consumption by conventional air conditioner and GSHP for different COPs and percentage of family usage. The possible power consumption by air conditioners in these states varies from minimum of 7.3 GW to 12,305 GW. The high power consuming states are Uttar Pradesh and Bihar. Fig. 13 shows the total power consumption by all the 10 states for space cooling by GSHP and conventional air conditioner. The minimum power consumption for cooling by air conditioner is 5506 GW and maximum possible power consumption for 50% of family use is 27,532 GW. The power consumption by GSHP varies from 4811 GW to 14,440 GW for COP of 3 with 10% family to COP of 5 with 50% of family usage.

4.2.2. Space cooling – power saving by GSHP

Fig. 14 shows the possible power saving by GSHP for different COPs and for different percentage of family usage. The minimum possible power saving by GSHP is 695 GW for GSHP with COP of 3 and for 10% of family use, for 30% and 50% of family use, the power savings are 2083 and 3472 GW respectively. Sikkim can save power by using GSHP in the range of 0.9–18 GW. Haryana can save between 39 GW and 727 GW. The details of power saving by individual state by GSHP at different COPs and different percentage of people use are tabulated in Table 5. At 50% family use the possible power saving is 13,092 GW with COP of 5. Based on the amount of power saving from the use of GSHP from maximum to minimum, all the 10 states can be ranked as, Uttar Pradesh, Bihar

Table 5
Power consumption for space cooling by AC and GSHP and power saving by GSHP.

States	Population (millions)	Families (millions)	Power consumption for summer season (90 days) by air conditioner (GW)			Power consumption and saving by GSHP for COP=3 (GW)						Power consumption by GSHP for COP=4 (GW)						Power consumption by GSHP for COP=5 (GW)					
			10%	30%	50%	10%		30%		50%		10%		30%		50%		10%		30%		50%	
						C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S	C	S
SK	0.6	0.12	7.3	21.9	36.6	6.4	0.9	19.2	2.7	32.0	4.6	4.8	2.5	14.4	7.5	24.0	12.6	3.8	3.4	11.5	10.4	19.2	17.4
AR	1.3	0.27	16.6	50.0	83.3	14.5	2.1	43.7	6.3	72.8	10.5	10.9	5.7	32.7	17.2	54.6	28.7	8.7	7.9	26.2	23.7	43.7	39.6
HP	6.8	1.37	82.6	248.0	413.4	72.2	10.4	216.7	31.2	361.3	52.1	54.2	28.4	162.6	85.4	271.0	142.3	43.3	39.3	130.1	117.9	216.8	196.6
UK	10.1	2.02	122.0	366.0	610.0	106.6	15.3	319.8	46.1	533.1	76.9	79.9	42.0	239.9	126.0	399.9	210.0	63.9	58.0	191.9	174.0	319.9	290.0
JK	12.5	2.50	151.3	454.0	756.7	132.2	19.0	396.7	57.2	661.2	95.4	99.2	52.1	297.6	156.3	496.0	260.6	79.3	71.9	238.1	215.8	396.8	359.8
HR	25.3	5.07	305.7	917.2	1528.7	267.1	38.5	801.5	116	1335.9	192.8	200.4	105	601.3	315.9	1002	526.5	160.3	145.3	481.0	436.1	801.8	726.9
PB	27.7	5.5	334.1	1002	1670.5	291.9	42.1	875.9	126	1459.8	210.6	219.0	115	657.1	345.2	1095	575.3	175.2	158.8	525.7	476.6	876.1	794.3
RJ	68.6	13.7	827	2482	4137.8	723.1	104	2169	313	3615.9	521.8	542.5	285	1627	855.0	2712	1425	434.0	393.5	1302	1180	2170	1967
BR	103.8	20.7	1251	3755	6259	1093	157	3281	473	5469	789	820.7	431	2462	1293	4103	2155.7	656.5	595.2	1969.7	1785.8	3282.9	2976.4
UP	199.5	39.9	2406	7220	12,034	2103	303	6310	910	10,516	1517.8	1577.9	828.9	4733.9	2486.8	7889.9	4144.8	1262.3	1144.5	3787.1	3433.6	6311.9	5722.7

SK: Sikkim, AR: Arunachal Pradesh, HP: Himachal Pradesh, UK: Uttarakhand, JK: Jammu and Kashmir, HR: Haryana, PB: Punjab, RJ: Rajasthan, BR: Bihar, UP: Uttar Pradesh, C: Consumption, S: Saving.

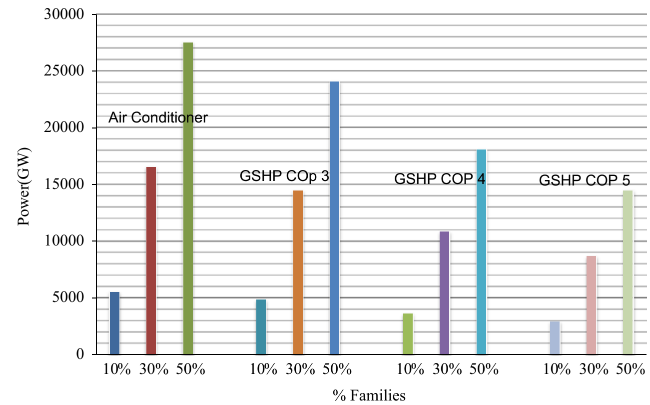

Fig. 13. Space cooling – power consumption by AC and GSHP.

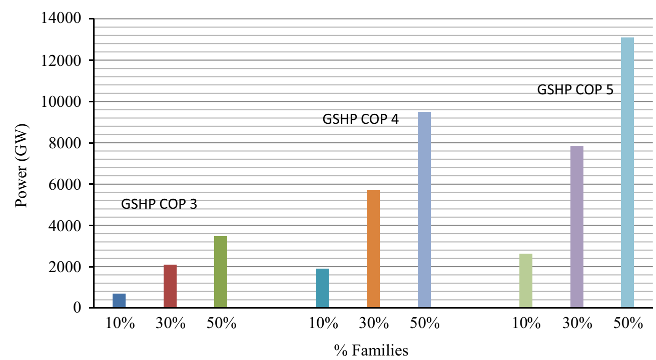

Fig. 14. Space cooling – power saving by GSHP.

and Rajasthan, Punjab, Haryana, Jammu and Kashmir, Uttarakhand, Himachal Pradesh, Arunachal Pradesh and Sikkim.

4.2.3. Space cooling – CO_2 produced

In general, the power consumption by conventional air conditioners will vary with their performance index. In this calculation we considered two star rated air conditioners to meet the cooling requirement. Table 6 shows the CO_2 produced by space cooling requirements. As per India's power generation pattern most of the power is being produced by coal based power plant, in that case the CO_2 produced by conventional air conditioner for 10% family is 3869 million kg and total CO_2 produced by conventional air conditioner for all the 10 states, for 10% family use is 4192 million kg and for 50% family use it is 20,959 million kg. The CO_2 produced by GSHP with COP 3 and for 10%, 30% and 50% of family use are 3663, 10,989, 18,315 million kg, respectively. The CO_2 produced by GSHP with a COP of 4 at 10%, 30% and 50% family use are 2748, 8244 and 13,740 million kg, respectively and for COP 5, it is 2199 million kg, 6595 million kg, 10,992 million kg of CO_2 produced by 10%, 30% and 50% of family use, respectively. Fig. 15 shows the overall power consumption by air conditioners and GSHP for different level of family usage and for different performance levels. The CO_2 produced by different energy sources like, coal, gas, oil, nuclear, hydro and renewable energy sources are presented as per the national electricity generation pattern in Table 6.

4.2.4. Space cooling – CO_2 saving by GSHP

Fig. 16 shows the possible CO_2 saving by GSHP for different percentage of family use and for different values of COPs. By using GSHP, the minimum possible CO_2 saving is 528 million kg and it can be increased to 9966 million kg, if the COP of the GSHP is increased to 5 and 50% of families are using GSHP for their cooling

Table 6
Space cooling CO_2 produced by AC and GSHP and CO_2 saving by GSHP.

CO_2 produced by different energy sources	CO_2 produced by Air Conditioner (million kg)			CO_2 produced by GSHP for COP=3 (million kg)			CO_2 produced by GSHP for COP=4 (million kg)			CO_2 produced by GSHP for COP=5 (million kg)		
	10%	30%	50%	10%	30%	50%	10%	30%	50%	10%	30%	50%
Coal	3868.9	11,606.7	19,344.5	3380.9	10,142.8	16,904.7	2536.4	7609.3	12,682.2	2029.1	6087.4	10,145.7
Gas	242.7	728.1	1213.5	212.1	636.3	1060.5	159.1	477.3	795.6	127.3	381.9	636.5
Oil	36.2	108.7	181.2	31.6	95.0	158.4	23.7	71.3	118.8	19.0	57.0	95.0
Hydro	13.7	41.1	68.6	11.9	35.9	59.9	8.9	26.9	44.9	7.1	21.5	35.9
Nuclear	9.3	27.9	46.5	8.1	24.3	40.6	6.0	18.2	30.4	4.8	14.6	24.3
Renewable Energy	20.8	62.4	104.0	18.1	54.5	90.9	13.6	40.9	68.2	10.9	32.7	54.5
Total CO_2 produced	4191.7	12,575.1	20,958.5	3663.0	10,989.1	18,315.3	2748.0	8244.2	13,740.3	2198.4	6595.3	10,992.3
CO_2 saving (million kg)				*528.6*	*1585.9*	*2643.2*	*1443.6*	*4330.9*	*7218.1*	*1993.2*	*5979.7*	*9966.2*

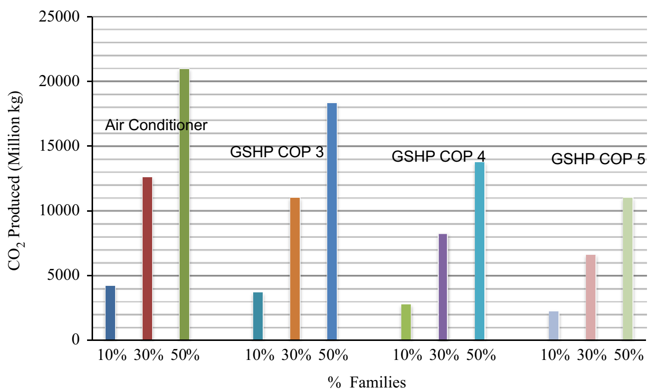

Fig. 15. Space cooling – CO_2 produced by AC and GSHP.

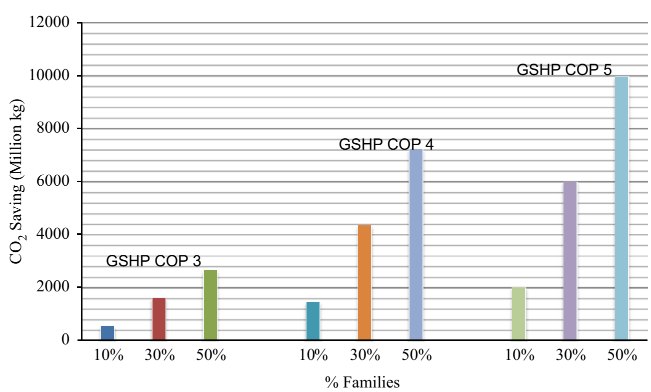

Fig. 16. Space cooling – CO_2 saving by GSHP.

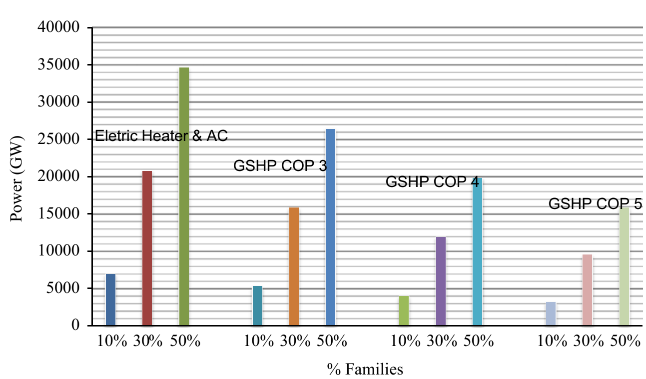

Fig. 17. Annual power consumption for space heating and cooling.

demand. Power consumption by 50% family using air conditioner is produced by nuclear power plant means then the CO_2 emission will be 1817 million kg. The majority of the CO_2 saving potential lies with high population states like Uttar Pradesh, Bihar and Rajasthan. A small state like Sikkim, Arunachal and Himachal also gets some possible benefits from GSHP but in these states most of the power is being generated by hydro thermal power plants.

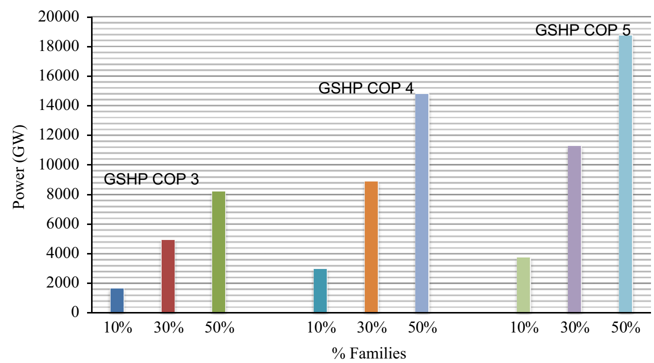

Fig. 18. Annual power saving by GSHP for space heating and cooling.

4.3. Annual power consumption for space heating and cooling

Majority of the states in India need both heating and cooling. At present most of these states are using conventional systems like electric heater and air conditioners for heating and cooling. Power consumption by this conventional system in a year for 10% family use is 6923 GW and for 50% of family use is 34,616 GW. For the same heating and cooling load, if GSHP is used then the possible power consumption for a GSHP with COP 3 at 10% family use is 5284 GW and for 50% of family usage it is around 26,421 GW. Fig. 17 depicts the power consumption by conventional system and GSHP. When the GSHP is operating at COP of 4 then the possible power consumption for 10%, 30%, and 50% families are 3964, 11,892, and 19,821 GW respectively. For GSHP COP of 5 power consumption are 3171, 9514 and 15,857 GW for 10%, 30% and 50% of family use.

4.4. Annual power saving by GSHP for space heating and cooling

The possible power saving by GSHP for both heating and cooling varies with the COP of GSHP. Fig. 18 shows the possible power saving by GSHP at different COPs, when GSHP is operating at COP 3, the power saving for 10%, 30% and 50 % families are 1639, 4917, and 8195 GW respectively. At COP 4, the power savings are 2959, 8877, and 14,796 GW for 10%, 30% and 50% families respectively. At COP 5, the power saving for 10%, 30% and 50 % families are 3752, 11,256 and 18,760 GW respectively. When GSHP is used the possible range of power saving varies from 1639 GW to 18,760 GW.

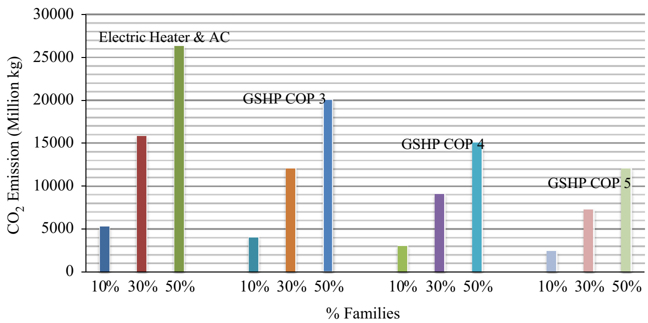

Fig. 19. Annual CO_2 emissions by electric heater, AC and GSHP for space heating and cooling.

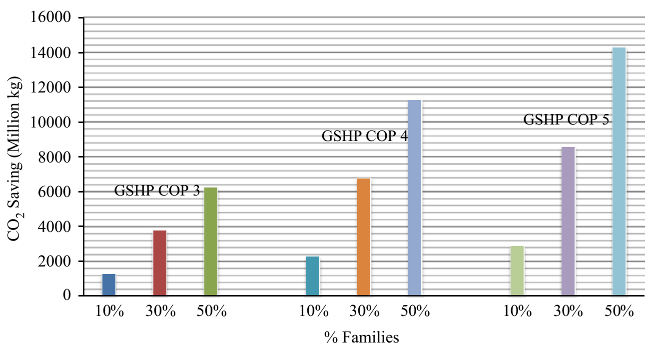

Fig. 20. Annual CO_2 saving by GSHP for space heating and cooling.

4.5. Annual CO_2 emission for cooling and heating

In India CO_2 emission is increasing year by year, the emission from building heating and cooling is at significant level. Fig. 19 shows the CO_2 emission by the 10 states by electric heater and air conditioner and GSHP at different COPs. For 10%, 30% and 50% family use the CO_2 emission by the use of electric heater and air conditioner are 5270, 15,811 and 26,352 million kg, respectively. Using GSHP with COP 3 for different level family use, the CO_2 emissions are 4022, 12,067 and 20,113 million kg. For GSHP with COP 4, the CO_2 emissions for 10% 30% and 50% families are 3017, 9053 and 15,088 million kg, respectively. The CO_2 emission for GSHP with COP 5 at 10%, 30% and 50% family use are 2414, 7243 and 12,071 million kg, respectively.

4.6. Annual CO_2 saving by GSHP for cooling and heating

In many countries GSHP has played a major role in saving the environment. In Asia, China is far ahead in using the GSHP technology for building heating and cooling and the government is also promoting this technology, for example, Beijing Olympic Village was completely space conditioned by GSHP technology. In India by using GSHP technology it can reduce its emission level, in a year by the use of GSHP technology for heating and cooling. India can reduce the production of CO_2 in a range between 1248 million kg and 14,281 million kg. Fig. 20 illustrates the annual CO_2 saving potential of GSHP system for space heating and cooling. When GSHP is operating at COP of 3, the possible reduction in CO_2 emissions are 1247 million kg for 10% family use, 3743 million kg for 30% family use and 6239 million kg for 50% family use. In the case of GSHP with COP 4, the possible reduction in CO_2 emissions are 2253, 6758 and 11,264 million kg for 10%, 30% and 50% family use. By the use of GSHP with COP 5, the CO_2 savings are 2856, 8569 and 14,281 million kg for 10%, 30% and 50% family use respectively.

5. Conclusions

India is a rapidly developing economy and its economic growth had profound effect on its building sector. Based on year round weather condition, about 10–12 states in India need both heating and cooling. In this paper 10 north and northeast states are considered for the analysis. For heating, the power consumption calculation of these states are divided into severe winter states and moderate winter states because heating requirement days vary in these two categories of states. Cooling requirement days for all the 10 states are considered as 90 days. In these 10 states for heating and cooling requirements, the conventional electric heater and air conditioners are assumed to be used. Based on a detailed analysis of the data obtained for both heating and cooling requirements of these 10 states, the following conclusions are arrived at:

- The power consumption by electric heater for space heating ranges from 1416 GW to 7085 GW; however for the same heating demand GSHP consumes electricity in the range 471–1416 GW, thus the use of GSHP results in saving of electricity about 67–80% in a year.
- In the case of cooling, the power consumption by air conditioner varies from 5506 to 27,532 GW, however for the same cooling demand the power consumption by GSHP varies from 4811 to 14,440 GW, resulting in a power saving of about 13–48% in a year.
- The conventional systems are emitting 5270–26,352 million kg of CO_2 in a year for space heating and cooling, but with the use of GSHP, the CO_2 emission ranges from 4022 to 12,071 million kg, resulting in a reduction of about 24–54% in a year.
- By the use of GSHP the annual saving in CO_2 varies from 1248 to 14,281 million kg and electricity saving ranges from 1639 to 18,760 GW. It is equivalent to an addition of 187–2141 MW power plant in a year.

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